Modern Computational Accelerator Physics

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Fermilab

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Calculating Particle Tunes and Synergia Results

Calculating Particle Tunes

- The simplest definition of tune is the number of full oscillations a particle experiences during the course of a single turn.
- Given a particle track, the Fast Fourier Transform makes it seemingly trivial to find the dominant frequency, and hence the tune.
  - numpy.fft.fft is the FFT function, which will return a complex vector
  - abs(vec) will return a vector of the absolute values of the complex elements of vec
  - numpy.argmax(vec) will return the index of the largest value in vec
  - The tune is just the position of the peak divided by the number of turns in the sample.

Calculating Particle Tunes (2)

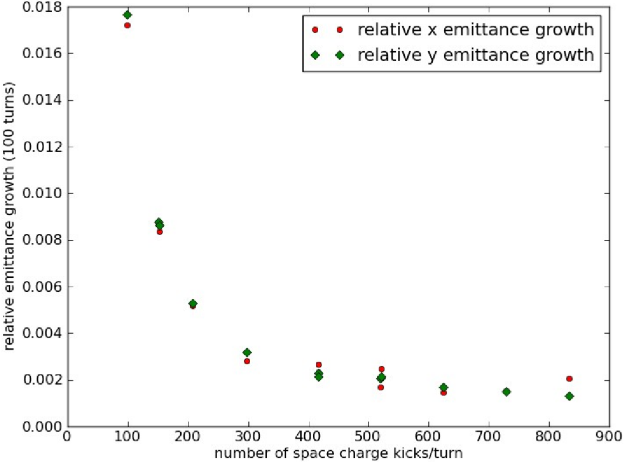
- Why did I say *seemingly* trivial?
  - There is usually noise in the lowest (few) frequency(ies).
  - Too many samples may lead to noise in other channels that will dominate the actual tune peak.
  - The NyquistShannon sampling theorem tells you that
    - you should only look in the lowest half of the FFT result.
    - you need at least twice as many samples per turn as the tune if you want to see the integer part.
    - you need at least two samples per turn if you are only interested in the fractional tune.

Applications: Fermilab Main Injector (Project X)

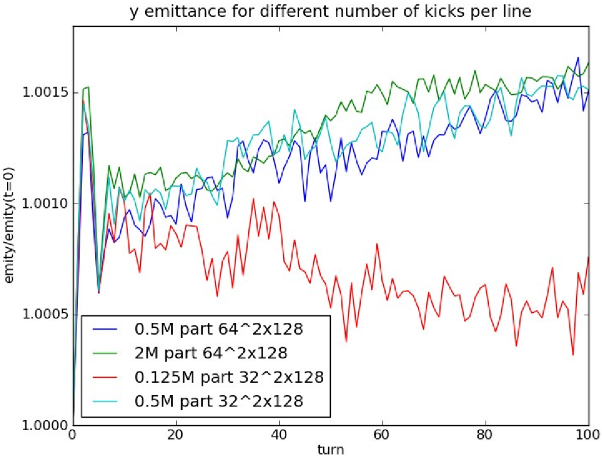
Eric Stern, JFA

- Significant effort spent understanding convergence of space charge calculation
  - grid size
  - number of macroparticles
  - number of kicks per turn
- Includes generation of nonlinearly-matched initial beam
  - very full RF bucket means very nonlinear longitudinal dynamics
  - using CHEF's arbitrary-order normal form calculation

MI kicks per turn study



MI grid and macroparticle study



Compromise between running time and accuracy:
0.5M macroparticles, 32x32x128 grid

Space charge and nonlinear optics studies for Mu2e[1]

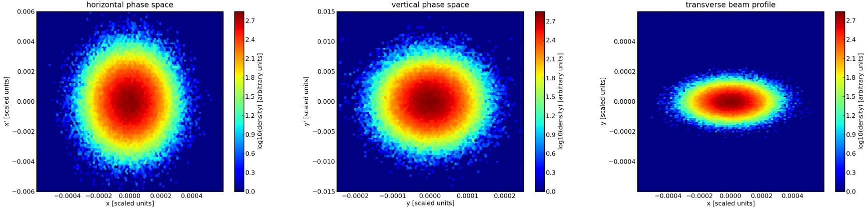
Motivation

- Beam to be extracted from Fermilab Debuncher using (nonlinear) resonant extraction
- Accumulator/Debuncher required to handle 10^5 times more particles than current operating conditions
  - Space charge is the biggest worry.

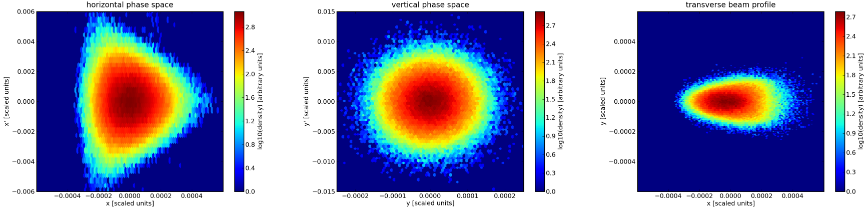
[1] J. Amundson, A. Macridin, L. Michelotti, C. S. Park, P. Spentzouris, E. Stern

Sextupoles without space charge

Beam with linear magnets only



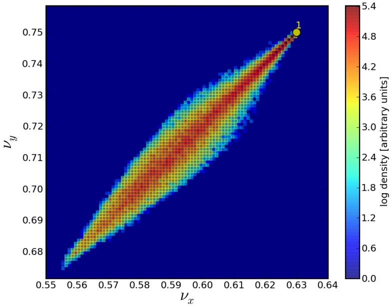
Beam with (nonlinear) sextupoles

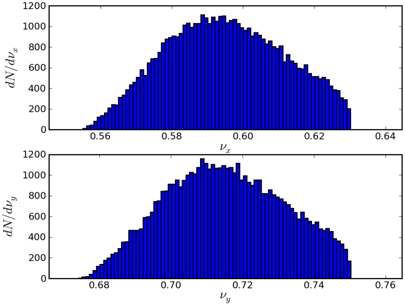


Nonlinear magnets distort the phase-space structure of the beam.

Effects of space charge without sextupoles

- In a fully linear linear problem, all particles have the same ("bare") tune.
- Space charge creates a "tune footprint"

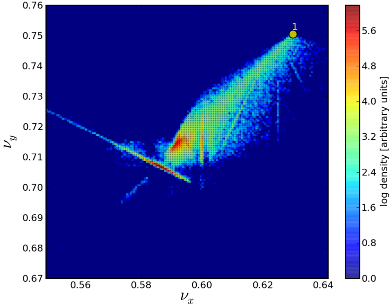


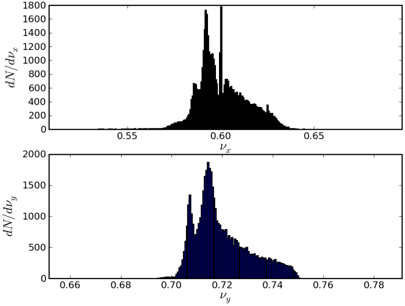


- Two-dimensional densities (colors) are plotted on a logarithmic scale
- One-dimensional densities are plotted on a linear scale
- Bin sizes are one unit of tune resolution

Combining sextupoles and space charge

Highly non-trivial interaction between the two effects...



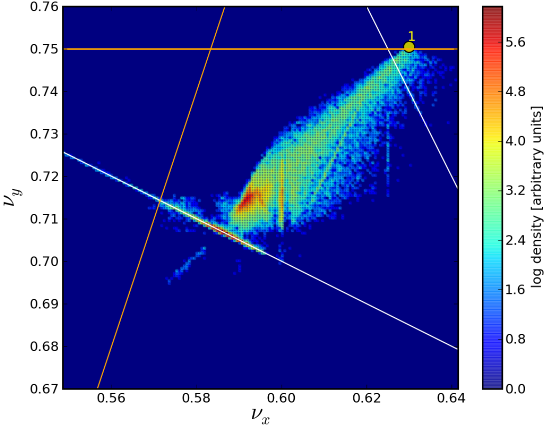


...leading to unacceptably large losses. Results are understood in terms of resonance theory. Resonances occur when

$$m + l\nu_x + q\nu_y = \nu_x$$

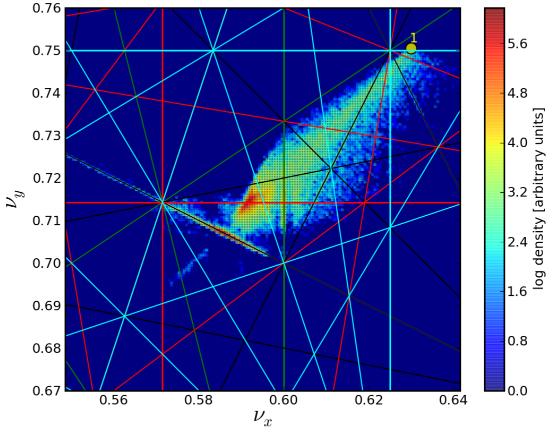
for integer m,l,q.

Resonance lines in the tune footprint



white	3^{rd}-order	black	6^{th}-order
orange	4^{th}-order	red	7^{th}-order
green	5^{th}-order	cyan	8^{th}-order

Resonance lines in the tune footprint



white 3^{rd}-order

orange 4^{th}-order

green 5^{th}-order

black 6^{th}-order

red 7^{th}-order

cyan 8^{th}-order

Applications: GSI SIS18 Benchmarking Exercise

- 71 steps/turn
- 7,100,000 steps
- 4,194,304 particles
- 29,779,558,400,000 particle-steps
- 1,238,158,540,800,000 calls to drift